High Beta and Enhanced Confinement in a Second Stable Core VH-Mode Advanced Tokamak

A. D. Turnbull, T. S. Taylor, Y. R. Lin-Liu, and H. St. John
General Atomics, San Diego, California 92186-9784

(Received 7 March 1994)

A new, enhanced performance tokamak regime, the second stable core VH-mode (SSC-VH), with a self-consistent VH-mode transport barrier and a large second stable core pressure gradient supported by negative central magnetic shear, is proposed. The SSC-VH is shown to have promising β limits simultaneously with enhanced confinement and a large, well-aligned bootstrap current fraction. Simulations show that a wall-stabilized high β, high-confinement SSC-VH can be maintained self-consistently in a steady state, by noninductive current drive.

PACS numbers: 52.55.Fa, 52.25.Fi, 52.55.Pi

The recent DT fusion experiments [1] in JET and TFTR have renewed interest in improving the economic viability of tokamak reactors. Recent work has shown that simultaneous achievement of high normalized β, $\beta_N \equiv \beta/(I/aB_0)$, high confinement enhancement, $H \equiv \tau/\tau_{\mathrm{I89P}}$, and a large, well-aligned bootstrap current fraction, $f_{\mathrm{bs}} = I_{\mathrm{bs}}/I$, offers the promise [2] of compact, more economically competitive, steady-state tokamak fusion reactor. Here, I is the total current (MA), a is the minor plasma radius (m), B_0 is the toroidal magnetic field (T), and τ_{I89P} is the ITER-89P L-mode confinement time [3]. I_{bs} is the bootstrap current, and by "well aligned" we mean that the bootstrap and total current *profiles* have approximately the same form.

Experimentally, several high performance tokamak operating regimes have been identified which demonstrate the feasibility of "advanced" operation above the Troyon limit [4], with $\beta_N \gtrsim 3.5$, H factors between 2 and 4, and with f_{bs} up to 70%. Although some of these advanced features have been achieved in individual discharges [5–8], the goal of simultaneous achievement of all three, which we refer to as advanced tokamak (AT) operation, has not yet been demonstrated. We present, here, a novel AT scenario in which this can be accomplished in steady-state operation.

The requirements of high confinement, magnetohydrodynamic (MHD) stability at high β, and good, well-aligned bootstrap current fractions are not easily reconcilable. Enhanced confinement at high β requires a large pressure gradient and an associated large bootstrap current density [9–11] j_{bs} in the high confinement region. This is true of all the experimentally observed high confinement ($H > 2$) regimes so far [5–8] and is consistent with the view that enhanced confinement arises from increased $E \times B$ shear [12] associated with the ion pressure gradient. If good alignment of the bootstrap current is also required, the resulting edge pressure gradient and current density are destabilizing to low n MHD modes [13]. For example, in the VH mode [6] ($H \simeq 4$), the transport barrier is related to the finite edge pressure gradient and an edge bootstrap current [14], which are also responsible for the relatively low β limit of $\beta_N \lesssim 3.5$; the VH-mode phase is generally terminated by a low n ideal MHD instability [14], driven by [15] the finite edge pressure gradient $p_{\mathrm{edge}} \equiv dp/d\Psi$ (Ψ is the poloidal flux) and current density j. This basic incompatibility must be resolved for the advanced tokamak concept to become a practical reality.

Here, we propose a configuration that has all three elements necessary for an advanced tokamak. The basic idea is to combine the essential features of the high performance DIII-D regimes [6–8], specifically the favorable core features of the second stable core [7] (SSC) and high [8] β_p configurations, with the VH-mode edge transport barrier, in a self-consistent fashion to arrive at a new configuration with superior β limit to the standard VH mode but which retains the VH-mode enhanced confinement. We call this the second stable core VH-mode (SSC-VH) configuration.

Experimentally, neither the VH mode nor the SSC reach a steady state—they continue to evolve into unstable MHD states which result in their termination. Thus it is necessary to show that the proposed SSC-VH configuration can be stably maintained. Using phenomenological transport models based on data from appropriate DIII-D and JET discharges, we show that the SSC-VH equilibrium can be maintained self-consistently in a steady state by a mix of noninductive fast wave (FW), neutral beam (NB), and electron cyclotron (EC) heating and current drive coupled to a large, well-aligned bootstrap current fraction.

In DIII-D, very high β has been obtained ($\beta > 10\%$) in SSC discharges [7] in which the negative central shear from an off-axis minimum in the safety factor q provided direct access to the second stability regime. These discharges have a large core pressure gradient with a high axial β value of $\beta_0 \equiv p_0/(B^2/2\mu_0) \sim 44\%$ and $\beta^* \equiv \langle p^2 \rangle^{1/2}/(B^2/2\mu_0) \sim 15\%$. High β^* is particularly favorable in a reactor since it implies higher fusion reactivity for a given volume-averaged β. A similar configuration, the so-called PEP mode [16], has also been observed in the JET tokamak, which also found improved energy confinement, consistent with neoclassical transport, in the reversed shear region.

The DIII-D SSC discharges typically have $q_0 \simeq 1.1$ and $q_{\min} \simeq 0.85$, and exhibit a saturated, rotating internal $m/n = 1/1$ kink, but remain in this configuration for several energy confinement times. The termination is usually due to the appearance of growing 2/1 and 3/2 modes which couple to the saturated 1/1 mode. Previous β optimization studies [17] in conjunction with the straight tokamak model [13], suggest a promising approach to improving the stability of this SSC. To lowest order, the stabilizing energy is proportional to [13] $(m - nq)^2$. Those surfaces where this vanishes can be eliminated [17] for the most dangerous modes by raising q_0 and $q_{\min}$. The most dangerous instabilities are the low $m, n = 1$ modes, followed by the $n = 2$ modes; the former are usually responsible for disruptions, whereas the latter are typically associated with β collapses, as well as the VH-mode termination (usually also marginal to the $n = 1$ mode) [15]. Higher n modes tend to be amenable to stabilization by minor modifications of the current profiles. By raising q everywhere above 2.5, the $m/n = 1/1$, 2/1, 3/2, and 5/2 modes are completely eliminated. Further stabilization of the higher order modes is then provided by ensuring that the shear near the remaining rational surfaces is large—either positive or negative—so that $(m - nq)$ is small only over a small region.

For an SSC with $q_{\min} > 2.5$, calculations [10,11,18] show that the most dangerous modes are eliminated and high β, and very high $\beta_N \equiv \beta^*/(I/aB)$, values can be stable. Furthermore, high β_p experiments [8] in DIII-D have verified that the predicted [17] stable windows exist for $q > 2$. Saturated $n = 1$ internal modes were sometimes observed in those experiments which correlated extremely well [8] with the predictions from the ideal MHD stability calculations using the GATO code [19]. However, these are eliminated in the SSC by providing sufficient negative central shear.

We then modify the SSC profiles with $q_{\min} > 2.5$ by making the edge pressure gradient and current density consistent with VH-mode operation. The resulting SSC-VH equilibrium with $\beta = 7.5\%$ and $\beta_N = 5.7$ was calculated for DIII-D parameters and is summarized in Table I and shown in Fig. 1. Here, $V_N(\Psi)$ is the volume contained within a flux surface Ψ. The q profile is nonmonotonic in the core, with $q_0 = 3.9$ and $q_{\min} = 2.6$. There is also a steep $p'_{\rm edge}$ consistent with that measured in VH-mode discharges. A key feature of our approach is that this pressure profile is calculated, along with the j profile, self-consistently in full 2D geometry from the coupled transport and auxiliary heating and current drive simulations. This is a significant advance over earlier simulations [20] in which it was shown that auxiliary current drive could provide the required profiles for a low current, high β_p, globally second stable scenario, but which did not include the transport modeling. The transport calculations here also show that $p'_{\rm edge}$ is associated with a sizable, well-aligned $j_{\rm bs}$. This is shown in Fig. 2. In this figure, $\rho \equiv (\Phi_N)^{1/2}$ is a radial variable used in the transport simulations, with Φ_N the normalized toroidal flux.

TABLE I. SSC-VH equilibrium parameters.

β_N	5.7
β_N^*	7.3
β_T	7.5%
β_p	2.8
H	3.5
$T_e^{\rm axis}$	8.5 keV
$T_i^{\rm axis}$	15 keV
I_p	1.6 MA
B_T	1.95 T
κ	2.1
q_{95}	6.5
ℓ_i	0.64
$\bar{n}$	5.7×10^{19}
$Z_{\rm eff}$	1.7

Low n ideal MHD stability calculations using the GATO code show that, with no wall, the equilibrium is unstable to a global, $n = 1$ pressure-driven mode. With stabilization from the DIII-D vacuum vessel, however, it was found to be *stable* to the ideal $n = 1$ and 2 kink modes. The lowest unstable mode is $n = 3$, which can be stabilized if necessary by uniformly lowering the pressure to $\beta_N = 5$, or by smaller local adjustments in the pressure gradient. This is a large improvement over the standard VH mode; $\beta = 7.5\%$ is significantly higher and $\beta_N = 5.7$ is well above the stability limit of 3.2 that is typical of the VH mode, even with stabilization from the DIII-D wall [14,15].

Ballooning stability calculations using the CAMINO code [21] show that the core is well in the second stability regime over a large part of the plasma volume out to a normalized poloidal flux of $\psi \sim 0.8$. (ψ is Ψ normalized to zero on axis and one at the edge.) This is characteristic

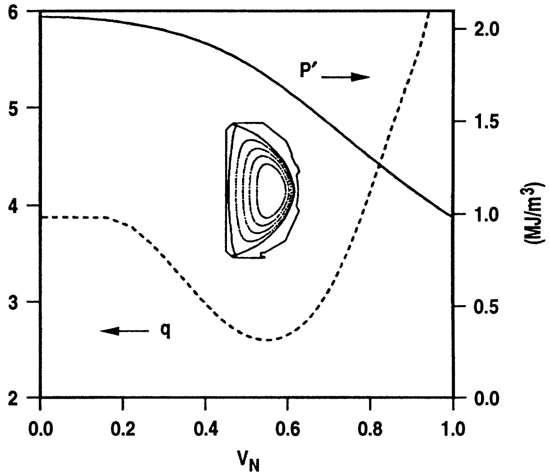

FIG. 1. Target profiles of $q(V_N)$ and $p'(V_N) \equiv dp/d\Psi$ for the SSC-VH simulation, with flux configuration (inset).

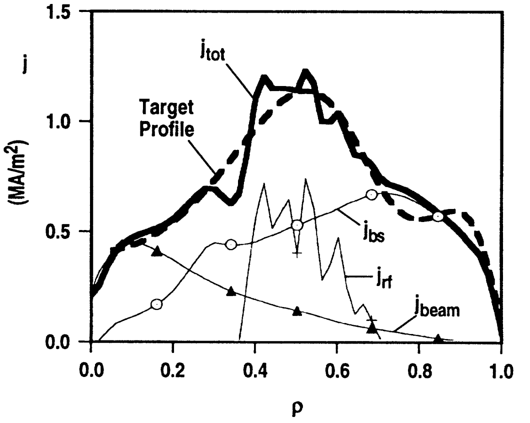

FIG. 2. Comparison of target and simulation $j(\rho)$ profiles showing EC, NB, bootstrap, and Ohmic contributions.

of the SSC profiles. Near $\psi \sim 0.9$, the profiles are first regime limited but at the very edge, second stability is again achieved.

We show that this configuration can be maintained in a steady state by an appropriate mix of noninductive FW, NB, and EC heating and current drive with a self-consistent contribution from j_{bs}. A simulation study was carried out using the ONETWO [22] transport code coupled to the rf packages FASTWAVE [23] and TORAY [24]. The ONETWO code evolves the electron and ion temperatures T_e, T_i, and the j profile for given transport coefficients χ_e and χ_i. The bootstrap current [25] and NB heating and current drive profiles are self-consistently computed within the code and the FW and EC heating and current drive profiles are computed by 2D ray tracing calculations in the FASTWAVE and TORAY codes.

The ONETWO code routinely provides an accurate description of the evolution of a wide variety of DIII-D discharges [22]. The TORAY and FASTWAVE codes also successfully predict [26] the measured noninductive current drive in DIII-D. In our simulation, the local transport coefficients were taken from power balance modeling of DIII-D and JET discharges. We assume only that these coefficients depend on the local equilibrium profiles so that, in the core, they correspond to SSC and PEP mode discharges, whereas, outside the reversed shear region, they coincide with the VH-mode transport coefficients. To impose this, the local transport coefficients $\chi_{e,i}$ are represented as simple fixed functions in the radial variable ρ. The resulting *steady-state* pressure and current density profiles were then found to be consistent with the fixed transport coefficients, so that the procedure is self-consistent.

The simulation was done for typical DIII-D parameters. Fixed VH-mode density and Z_{eff} profiles, with line-averaged values of $\overline{n} = 0.57 \times 10^{20}\ \text{m}^{-3}$ and $\overline{Z}_{\text{eff}} = 1.7$, were used. The electron thermal diffusivity χ_e is given by the INTOR scaling [27]. The ion thermal transport χ_i is taken to be neoclassical at the core and rising to 5 times the neoclassical value near the edge. This model captures the essential features observed in DIII-D and JET, namely the neoclassical transport in the reversed shear region [16] and the radial variation obtained from analysis of DIII-D VH-mode discharges [10,14].

The results of the simulation are summarized in Table II and Fig. 2. The 120 MHz fast waves are required only for electron heating in the core region. The 110 GHz X-mode electron cyclotron waves provide off-axis heating and current drive (ECH and ECCD) at $\rho \sim 0.5$. This noninductive ECCD is consistent with measured [26] ECCD in DIII-D L-mode discharges based on the scaling of the current drive efficiency with T_e. Neutral beams then provide ion heating and additional central current drive. Figure 2 shows the simulated NBCD and ECCD contributions to j (j_{beam} and j_{rf}), as well as the self-consistent contribution from j_{bs}. The thick broken line represents the initial target equilibrium and the thick solid line is the total current profile computed from the transport simulations. The overall features of the profile are well reproduced, including large edge bootstrap current.

The confinement enhancement factor was found from the transport calculations to be $\tau_E/\tau_{\text{189P}} \simeq 3.5$. This enhancement is consistent with the experimentally obtained VH-mode confinement values. The power delivered to the plasma and respective contributions to the total current are give in Table II. The bootstrap current contributes two-thirds of the total; this is important in minimizing the total required current-drive power. The total auxiliary power of 20 MW is reasonable and attainable using present-day technology.

In summary, we have shown that the most desirable features of the high performance operating modes observed in DIII-D can be successfully combined in such a way as to retain the high confinement, but eliminate the MHD instabilities that terminate the original high performance modes. We have then shown that a self-consistent transport and noninductive heating and current-drive simulation permits a steady state so that this new proposed configuration *can be maintained with high β, high confinement, and a large, reasonably well-aligned bootstrap current fraction.*

The β limit is much greater than that in conventional VH-mode discharges. Wall stabilization from the DIII-D wall is necessary, however, to achieve this large gain in β and β^*. Recent studies [28] have shown that *complete*

TABLE II. Current drive power requirements.

	Power (MW)	Current (MA)
FW	6.5	0.0
EC	7.0	0.35
NB	6.5	0.25
BS	(NA)	1.07 (67%)
OH	(NA)	−0.07
Total	20	1.5

wall stabilization is actually possible if the plasma is rotating at some fraction of the sound speed. With unbalanced neutral beam injection, this can easily be satisfied.

The crucial distinguishing feature of our study is that the profiles are required to be internally consistent with the transport. This, for example, implies that p'_{edge}, obtained from the transport simulations, must be nonzero. The resulting second stability near the edge, in turn, appears to be a necessary condition for the existence of the VH-mode transport barrier [9,14]. Another important illustration of the fundamental limitations that the self-consistency constraint imposes is that the pressure profile peakedness is limited by the local core transport. Sensitivity studies indicate that the steady-state profiles are largely insensitive to the *details* of the local transport model over the bulk of the plasma and we have not been able to significantly increase the peaking factor with any transport model that is consistent with the experimentally observed transport in VH and PEP mode. Nevertheless, anomalous "nonlocal" processes, such as an inward heat pinch, might result in significantly higher peaking factors, thereby gaining the full advantage of the second stable core in terms of fusion yields.

There is a great deal of potential for optimizing the SSC-VH. In addition to the usual parameters, one can optimize β or β^* by extending the volume of the reversed shear region, and by varying q_0 and $q_{\min}$. Progress is being made in this optimization but is beyond the scope of this Letter. Given the good confinement and stability properties of the initial, essentially unoptimized configuration described here, we believe that the SSC-VH will open up a new avenue of potential high β and high confinement advanced tokamak regimes to be explored in both DIII-D and TPX [29], as well as in other future AT experiments.

We are indebted to Dr. M. S. Chu for providing the ballooning calculations used in this work. This is a report of work and research sponsored by the U. S. Department of Energy under Contract No. DE-AC03-89ER51114 and Grant No. DE-FG03-92ER54150.

---

[1] The JET Team, Nucl. Fusion **32**, 187 (1992); J.D. Strachan *et al.*, Phys. Rev. Lett. **72**, 3526 (1994).

[2] J.D. Galambos, L.J. Perkins, and S.W. Haney, Nucl. Fusion (to be published).

[3] P.N. Yushmanov *et al.*, Nucl. Fusion **30**, 1999 (1990).

[4] F. Troyon *et al.*, Plasma Phys. Controlled Fusion **26**, 209 (1984).

[5] L. Lao *et al.*, Phys. Rev. Lett. **70**, 3435 (1993); J.S. deGrassie *et al.*, in *Proceedings of the Conference on Controlled Fusion and Plasma Physics, Lisboa, 1993* (European Physical Society, Geneva, 1993), Vol. III, p. 965.

[6] G.L. Jackson *et al.*, Phys. Rev. Lett. **67**, 3098 (1991).

[7] E.A. Lazarus *et al.*, Phys. Fluids B **4**, 3644 (1992).

[8] P.A. Politzer *et al.*, Phys. Plasmas **1**, 1545 (1994).

[9] T.S. Taylor *et al.*, in *Proceeding of the Conference on Plasma Physics and Controlled Nuclear Fusion Research, Washington, 1990* (International Atomic Energy Agency, Vienna, 1991), Vol. 1, p. 177.

[10] V.S. Chan *et al.*, in Proceedings of the 1993 International Sherwood Fusion Theory Conference, Newport, 1993 (unpublished), Paper No. 1C26; T.S. Taylor *et al.*, Bull. Am. Phys. Soc. **38**, 1936 (1993).

[11] T.S. Taylor *et al.*, in Proceedings of ITC-5, Toki, 1993 (to be published); TS. Taylor *et al.*, Plasma Phys. Controlled Fusion (to be published).

[12] K.H. Burrell *et al.*, Phys. Plasmas **1**, 1536 (1994); GM. Staebler *et al.*, Phys. Plasmas **1**, 1909 (1994).

[13] J.A. Wesson, Nucl. Fusion **18**, 87 (1978); J.P. Freidberg, Rev. Mod. Phys. **54**, 801 (1982).

[14] T.S. Taylor *et al.*, in *Proceedings of the Conference on Plasma Physics and Controlled Nuclear Fusion Research, Würzburg, 1992* (International Atomic Energy Agency, Vienna, 1993), Vol. 1, p. 167.

[15] E.J. Strait *et al.*, in *Proceedings of the Conference on Controlled Fusion and Plasma Physics, Lisboa, 1993* (European Physical Society, Geneva, 1993), Vol. I, p. 211.

[16] B. Tubbing *et al.*, Nucl. Fusion **31**, 839 (1991); M. Hugon *et al.*, Nucl. Fusion **32**, 33 (1992).

[17] A.D. Turnbull *et al.*, Nucl. Fusion **29**, 629 (1989).

[18] C. Kessell *et al.*, Phys. Rev. Lett. **72**, 1212 (1994); J. Manickam *et al.*, Phys. Plasmas **1**, 1601 (1994).

[19] L.C. Bernard *et al.*, Comput. Phys. Commun. **24**, 377 (1981).

[20] P.T. Bonoli *et al.*, Nucl. Fusion **30**, 533 (1990).

[21] M.S. Chance, in *Proceeding of the Conference on Theory of Fusion Plasmas, Varenna, 1987* (Editrice Compositori, Bologna, 1987), p. 87.

[22] H. St. John *et al.*, in *Proceedings of the Conference on Controlled Fusion and Plasma Physics, Lisboa, 1993* (European Physical Society, Geneva, 1993), Vol. I, p. 99.

[23] S.C. Chiu *et al.*, Nucl Fusion **29**, 2175 (1989).

[24] K. Matsuda, IEEE Trans. Plasma Sci. **17**, 6 (1989).

[25] S. Hirschman, Phys. Fluids **21**, 8 (1978).

[26] R.I. Pinsker *et al.*, in *Proceeding of the Conference on Plasma Physics and Controlled Nuclear Fusion Research, Würzburg, 1992* (International Atomic Energy Agency, Vienna, 1993), Vol. 1, p. 683; V.V. Alikaev *et al.*, *ibid.* p. 627.

[27] J.A. Wesson, *Tokamaks* (Clarendon Press, Oxford, 1987), p. 85.

[28] A.D. Turnbull *et al.*, in *Proceeding of the Conference on Plasma Physics and Controlled Nuclear Fusion Research, Seville, 1994* (International Atomic Energy Agency, Vienna, to be published); A. Bondeson and D.J. Ward, Phys. Rev. Lett. **72**, 2709 (1993).

[29] R.J. Goldston *et al.*, in *Proceedings of the Conference on Controlled Fusion and Plasma Physics, Lisboa, 1993* (European Physical Society, Geneva, 1993), Vol. I, p. 319.